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A System Dynamics Simulation Model for a Four-rank Military Workforce

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ABSTRACT

This report presents a system dynamics simulation model for a four-rank military workforce, that includes both the combat and training components. A qualitative analysis using a Causal Loop Diagram displays the feedback loop structure of the workforce and its impacts on the management of training. The simulation model is applicable to strategic training policy design and analysis, in answering 'what if ...' questions, and workforce planning in expanding military organisations.

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Executive Summary

This report forms part of the Training Force Sustainment Model studies requested by Training Command – Army.

The military workforce is known for its ‘closedness’ and hierarchical nature. The workforce is a closed system because essentially all recruitment is at the entry level. The workforce is strictly hierarchical in that higher rank trainees must be promoted from one rank below the destination rank. This report presents a system dynamics (SD) simulation study of a four-rank military workforce training management system. SD focuses on the circular causality and information feedback nature of systems in order to understand their behaviour over time.

Starting with the generic properties of closedness and hierarchy inherent in any military organisation, a Causal Loop Diagram (CLD) portrays the feedback structure for a four-rank military workforce. Based on the CLD constructed, a detailed intra-rank and inter-rank loop analysis reveals possible effects on training management when the system experiences an external disturbance such as a demand for expansion. More specifically, the CLD depicts the following consequences of the closedness and the hierarchical nature:

- Increased training demand at a higher rank causing training demands to increase at all lower ranks;
- The intention to expand the Combat Force (CF) could lead to its temporary reduction; and
- Depending on the instructor rank-structure, an increased training demand at a lower rank can, in principle, cause training demands to increase at higher ranks.

The report then proceeds to display an SD simulation model for quantitative analysis of an arbitrary four-rank military workforce. The utility of the SD model is demonstrated in three aspects:

- When applied to policy analysis, the model shows that a short-term reactive policy can lead to a ‘bullwhip’ effect. This amplified oscillating behavior in the CF workforce occurs even though the expansion target follows step functions and does not oscillate;
- When the human resource is constrained, or a system parameter, such as the separation rate, deviates from its average value, the model shows its ability to answer ‘what if ...’ questions; and
- Finally, the model exhibits its usefulness as a planning tool for expanding a military organisation.

The SD simulation model offers the workforce managers and the training planners, in particular, an analytic tool with which they can test different control policies and system parameters to improve system performance. This will produce a system capable of providing the right number of the right (qualified) people at the right time.

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Glossary

| | |
|------|----------------------------------|
| B | balancing |
| CF | Combat Force |
| CLD | Causal Loop Diagram |
| R | reinforcing |
| SD | Systems Dynamics |
| SFD | Stock Flow Diagram |
| TC-A | Training Command – Army |
| TFSM | Training Force Sustainment Model |

1. Introduction

Training Command-Army (TC-A) tasked DSTO to develop an Operations Research tool for strategic policy planning, the Training Force Sustainment Model (TFSM), to identify critical human resource issues in the ability of a training system to meet training demand. Well managed human resources in an organisation require good planning of the consequent training demand. The training system needs to meet the training demand to ensure a sufficient supply of competent personnel at the specified time at the minimum cost as specified by the human resources plan.

In a previous report, an analytical solution was developed to implement TC-A's training plan for an expanding military organisation [1]. Ref [1] was based on TC-A's training plan which assumes that the instructional force would not return to the operational force. However, when a training system is closed (where there is no access to external instructors or previously experienced operational staff) the assumptions of TC-A's training plan may not be valid. A subsequent report [2] investigated the closed training-force situation and a more efficient training plan for that situation was developed. Two mathematical models were constructed and two corresponding application tools were developed for the implementation of the recommended training plan [2].

It is noted that in [1] and [2], there is an additional assumption that the training system will meet the human resources demand in a single time-step. By a single time-step we mean a period of constant numbers of trainees and instructors, as well as a single graduation or separation event. The models of [1] and [2] therefore provide solutions with parameters that are independent of time (that is, they are 'static'), and hence are not intended for the investigation of a dynamic (time-dependent) response of the training system. Hence what is needed is a model that provides guidance of an ongoing and continuous nature that would guide policy design so as to handle 'shocks', such as: fluctuations in officer separation rates; fluctuations of trainee graduation rates; shortages of new recruits; shortages of promotion-qualified officers.

There are a number of approaches to investigate dynamic responses of workforce systems. In this report we have chosen system dynamics (SD) as the preferred approach because of its broad application in workforce management[3]. SD is a continuous simulation approach which allows the quantities of interest, or state variables, to change continuously as time progresses [4]. SD is concerned with the overall (aggregate and trend) system behaviour under the influence of policies and is less concerned with fine details than Discrete Event Simulation where state variables change only at discrete points in time [4, 5]. In addition, the relatively large numbers of trainees allows the aggregation of components of the system. The numerous short courses involved in Army training, and the long periods of time considered in this report enable an approximation of the Army training system to be investigated as if it were a continuous system.

The SD simulation model in this report takes a 'what if ...' approach to determining optimal policies for a robust workforce system. SD, like any simulation approach (including spreadsheets), is suited to the rapid formulation of a model that then enables the end user to conduct many trials while varying parameters. The process typically results in the end user gaining insights into the operation of the system, and hopefully finding the optimal policies. Here, by 'policies' we mean decision rules to specify actions

to achieve given goals [5]. For a system to be ‘robust’, we mean a system which is capable of defending itself against, or recovering from, fluctuations and shocks [3]. More specifically, in this report, the SD simulation describes the time-varying behaviours of officer and trainee numbers, and proposes possible solutions to improve the system performance when unexpected disturbances occur.

The report is organised as follows. Section 2 describes some elementary SD terminologies used in subsequent sections. An SD causal-loop diagram analysis of military workforce, which is an extension of the previous work [6], is presented in section 3. Section 4 presents an SD simulation model using Powersim Studio (Powersim Software 2005). The SD simulation model is then applied to a representative four-rank Defence workforce to explore optimal policies. Finally, section 5 presents the following conclusions: the intention to expand the combat force (CF) could lead to its temporary reduction; a short-term reactive policy is likely to lead to amplified oscillating behaviour in CF even though the expansion target follows non-oscillatory step functions. The utility of the SD model as an analysis tool and a planning tool is demonstrated by examples. It is recommended that, using actual Army data, this approach is incorporated as part of normal Army long-term planning, and may possibly be incorporated as part of other planning tools – such as the Army Sustainment Model. To reach this point, further work in development is needed. With some modification, the SD model in this paper is also relevant to other branches of Defence.

2. System Dynamics

As one of the computer-based simulation modelling methodologies, SD, initially named Industrial Dynamics [7], is defined as ‘the study of the information-feedback characteristics of industrial activity to show how organisational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise’ [7].

The focus of SD study is the structure of process and information, which is collectively referred to as the structure of information feedback loops in management systems [8]. ‘Intuitively, a feedback loop exists when information resulting from some action travels through a system and eventually returns in some form to its point of origin, potentially influencing future action’ [9]. Mathematically, feedback is the phenomenon where changes in the values of a variable indirectly influence future values of the same variable [10]. The structure of information feedback loops is assumed as the direct determinant of system behaviour over time [5, 8, 9]. ‘SD can be viewed as a theory of structure’ [11] to guide the policy design processes.

2.1 System Dynamics modelling fundamentals

The function of any system, be it natural or managed, is the transformation of resources [12]. For example, the function of a military training system is to transform the trainees into qualified soldiers or officers. System state variables, e.g., the numbers of trainees in a multi-rank training system, describe the resource status at any given point of time during the transformation process. SD refers to state variables as *levels* or *stocks*. Levels are observable and measurable, and their patterns of change over time completely

define the system dynamical behaviour. In SD, levels will rise and fall by inflows and outflows.

In our military training system model, the number of trainees will rise by the inflow of trainees recruited, and fall by the outflow of graduates. The inflows and outflows are referred to as *rate* or *flow variables*, which are the driving forces of the dynamics of the system. We note that level and stock can be used interchangeably, and similarly for rate and flow [13].

SD modelling is focused on the modelling of flows to explore policy impacts on system performance. System policies specify how the information about the values of levels is used to determine system flows. For example, the information about the actual number of staff in the defence workforce will be used in the policy of ‘eliminating the gap between the desired and actual workforce’ to determine the flow variable of yearly recruitment.

In the SD modelling world, systems are composed of resources and information. Resource flows cause the changes of resource levels. The information about the levels of resources flows back to the decision point to control the resource flows. It is the information flow, with possible distortion and time delay, that converts the open loop into an information feedback closed loop [14]. SD characterises *any* business process with three types of building blocks: stocks, flows and information [10], and analyses observed patterns of system behaviour in terms of structure of feedback loops.

When dealing with loop structures of systems, SD employs diagramming tools to demonstrate the existence of circular chains of cause-and-effect, and the system features [10]. Two diagramming tools used in SD modelling are the Causal Loop Diagram (CLD) and the Stock Flow Diagram (SFD).

2.2 System Dynamics diagramming tools

CLD is used in SD modelling to illustrate the cause and effect relationships in feedback structures of a system.

A CLD consists of cause and effects elements, represented by letters, and causal links, represented by arrows. A causal link connects a cause element, X, at the tail of the arrow to an effect element, Y, at the head of the arrow. Each causal link is either positive (+) or negative (-), called link polarity to indicate how the dependent (effect) variable Y changes when the independent (cause) variable X changes [15, 16]. A positive link from X to Y means that either X adds to Y, or a change in X results in a change in Y in the same direction [17]. Similarly, a negative link from X to Y means that either X subtracts from Y or a change in X results in change in Y in the opposite direction [17]. The sign of a feedback loop is determined by the signs of all links in the loop. More specifically, a loop is called positive or reinforcing (R) if it contains an even number of negative causal links; a loop is called negative or balancing (B) if it contains an odd number of negative causal links [15]. While a reinforcing loop tends to create change that drives the system away from its original condition, a balancing loop tends to create change that drives the system toward its original condition or toward a goal [18]. It is stated that ‘All systems, no matter how complex, consist of a network of positive and negative feedbacks, and all dynamics arise from the interaction of these loops with one another’ [15]. Figure 1 shows a simple CLD.

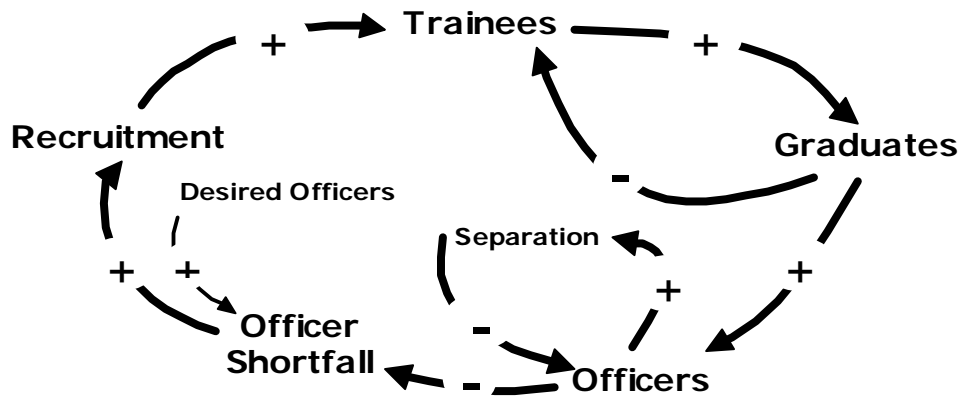


Figure 1. The CLD for officer training

Figure 1 illustrates the structure of a simple officer training system. For this system, management has set the goal of the system, i.e., the desired number of officers. The difference between the goal and the actual number of officers defines the officer shortfall. As the officer shortfall is increased, more recruitment is required. Increased recruitment leads to more trainees, and therefore more graduates. An increase in the number of graduates increases the actual number of officers, which mitigates the officer shortfall. This circumambient loop is balancing. The second B loop illustrates the causal relationship between trainees and graduates. The third B loop represents a relationship between the actual number of officers and separation. Separation is the number of officers leaving the defence force, which is modelled as the proportion of the magnitude of the actual officer stock [5, 14]. Separation reduces the actual number of officers, which can increase the Officer Shortfall to trigger recruitment. On the other hand, a larger officer base means a higher separation. CLD will be used in analysing a four-rank defence workforce to capture the special properties of military workforce.

Traditionally, CLD is used as a qualitative analysis tool, mainly at the initial stage of SD studies for model conceptualisation [16, 19]. Alternatively, CLD is suggested as a tool used in the later stage of SD studies to explain the quantitative results after a simulation model has been built and studied [20]. While the advantage of CLD is the simplicity of its diagrammatic conventions for representing and communicating the major circular causality mechanism [21], this simplicity is a limitation because it does not distinguish between the different types of variables such as stocks, flows and information [9, 21]. SD uses SFD as the basis for building simulation models for quantitative analyses. Figure 2 is an SFD for the officer training system in Figure 1.

The SFD in Figure 2 is created by the SD software Powersim Studio. In Studio, boxes represent levels. Double arrows represent flows (resource or material). Single arrows represent information links (or information flows). The cloud-like symbols to the left of the Recruitment flow and to the right of the Separation flow are the source and the sink, respectively. The source and the sink mark the boundary of the system. Circles represent auxiliary variables, which are introduced to combine different information flows as an intermediate step of calculation. Diamonds represent constants, which are set at the beginning of the simulation run and do not change throughout the simulation, unless modellers intervene manually.

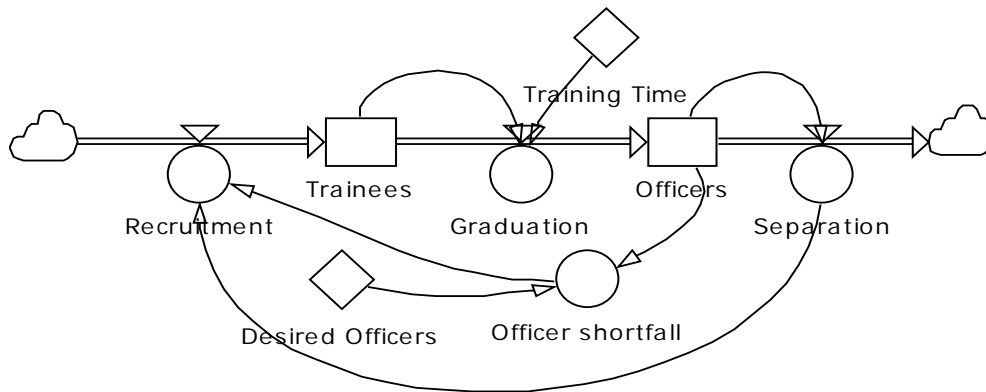


Figure 2. The SFD for officer training, the same system described by the CLD

In Figure 2, the two levels are numbers of trainees and officers, measured in people. The Trainee level is fed by the Recruitment flow (from a source) and is depleted by the Graduation flow. The Officer level is replenished by people who successfully complete their training, i.e., the inflow Graduation, and is depleted by the outflow Separation (into a sink). Two constants, Desired Officers and Training Time, denote the goal of the system and the time required to complete the training, respectively.

There are several information links that represent where and how the information is used to formulate system policies or controls. In Figure 2, the information about the actual number of officers and the Desired Officers leads to the determination of the auxiliary variable Officer Shortfall. Two information links, connecting the outflow Separation and the auxiliary variable Officer Shortfall to the flow Recruitment, announce that this system policy is to recruit enough people for training to fill the vacancy due to separation and to eliminate any officer shortfall.

Besides the CLD and SFD tools described above, another diagramming convention in SD practice is the Influence Diagram [3, 12, 14]. The Influence Diagram has an enriched library of symbols to show details of system structures, and is viewed as a tool lying somewhere between CLD and SFD [3]. Nevertheless, the majority of SD practitioners prefer the use of two clear diagramming approaches [21] and consider Influence Diagram as a synonym for CLD [9]. What is more, it is interesting to note that in Decision Analysis, there is also a graphic tool called the Influence Diagram, which was developed in the early 1980s[22] and is still an ongoing research topic [23] with a range of applications such as multi-agent modelling [24], solving games [25], and multiple objective and tradeoff analysis [26]. This report employs the established CLD and SFD formality to analyse a four-rank defence workforce in the following sections.

3. Causal Loop Analysis of the Military Workforce

This section is an extension of the previous CLD analysis of defence workforce planning [6].

The military workforce is known for its closedness and hierarchical nature. The workforce is a closed system because all recruitment is at the entry level of the officers or soldiers. Senior officers, instructors, and senior soldiers are produced within the system by training and promotion rather than recruited from outside [27]. The workforce is strictly hierarchical in that higher rank trainees must be from one rank below the destination rank. Moreover, two mechanisms in management of promotion should be recognised: a push flow and a pull flow. A pull flow refers to the promotion policy in which promotion is seen as the consequences of vacancies at the destination status, while in a push flow the constraint due to vacancy availability does not apply. The promotion for an Army officer *'will only be approved when a suitable establishment vacancy exists at the next rank'* [28] and therefore is working only as a pull flow. The impact of closedness, strict hierarchy and the pull-flow promotion on the planning of Army workforce, and the Training Force in particular is examined by analysing the CLD in Figure 3.

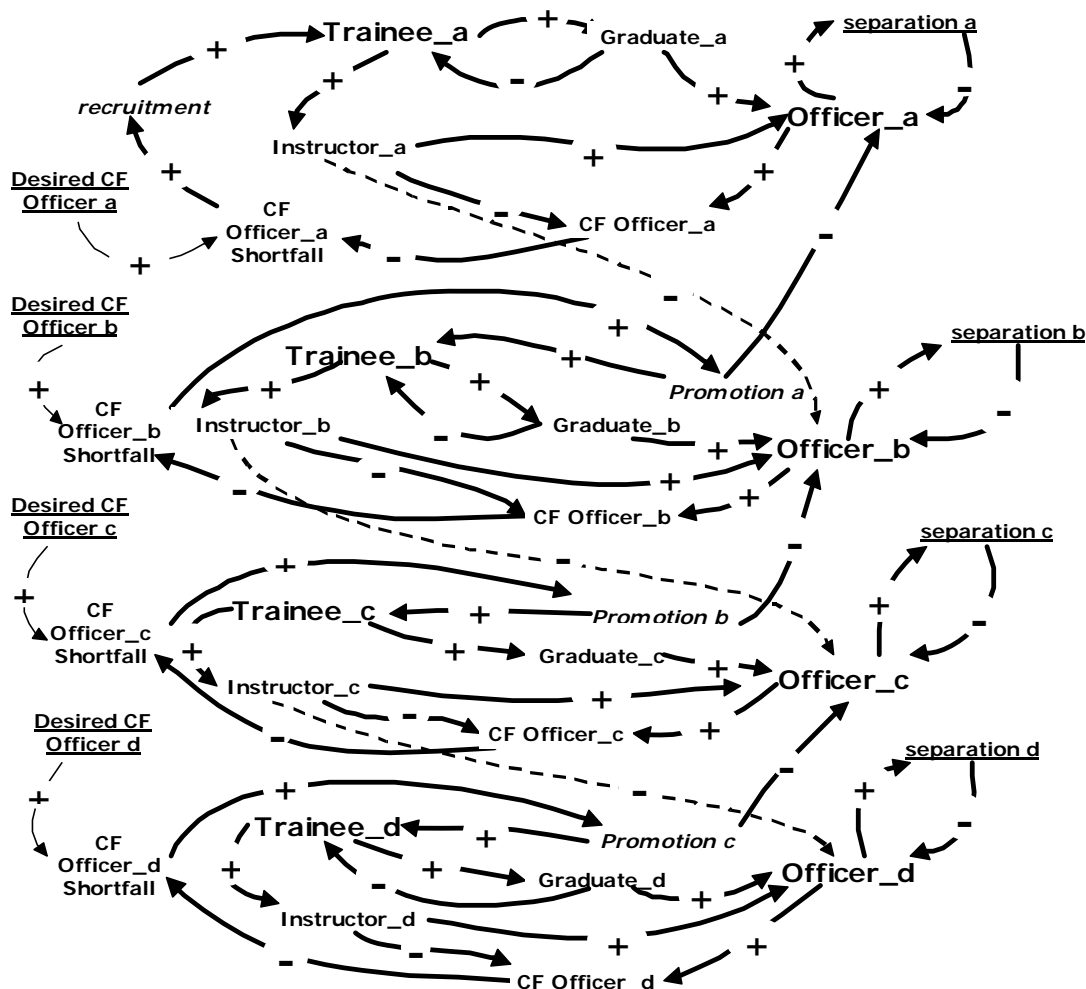


Figure 3. The CLD description of a Four-Rank workforce

The CFD depicts the human resource mobility in a four-rank officer training workforce, which consists of four ranks of *a*, *b*, *c* and *d* with the rank *d* as the highest. The goal of the system is to sustain the CF at a desired level (e.g. specified by the parameter Desired CF Officer_a for *a*-rank, ... etc.) through training. The CF officers and Instructors are discriminated explicitly. While the graduates after successful training join the officer pool to replenish any vacancies in CF, a need for Instructors can reduce the number of CF officers.

Figure 3 shows the following *intra*-rank loops:

1. B Loop: Officer_a → separation_a → Officer_a;
2. B Loop: Trainee_a → Graduate_a → Trainee_a;
3. B Loop: CF Officer_a → CF Officer_a Shortfall → recruitment → Trainee_a → Graduate_a → Officer_a → CF Officer_a;
4. B Loop: CF Officer_a → CF Officer_a Shortfall → recruitment → Trainee_a → Instructor_a → Officer_a → CF Officer_a;
5. R Loop: CF Officer_a → CF Officer_a Shortfall → recruitment → Trainee_a → Instructor_a → CF Officer_a.

Notice that there are two loops involving Instructor_a. The 5th R Loop shows the following cause-effect relationship. The increase of the shortfall in *a*-rank CF officers causes an increase in recruitment and therefore an increase of number of trainees. However, the increased number of trainees requires more instructors who must be from higher rank officers because of the closedness and the hierarchical nature of military organisation. If we assume that the instructors are from one rank above that of trainees, the loop states that the intention to increase the number of *a*-rank CF officers could lead to its temporary reduction due to shifting them from CF to work as instructors. The 4th loop declares that while instructors are non-combat officers, they are still part of the officer pool and therefore can join the CF if needed.

While the lowest *a*-rank trainees are recruited from outside of the workforce, the higher rank trainees are from the pool of CF officers for promotion-training. The consequence of increased promotion, as indicated by the inter-rank link (e.g., the link from Promotion_a to Officers_a), is to reduce the number of officers at the next lower rank, and therefore to trigger all loops in lower ranks in a chain-like manner. The fact that increased training demand at a high rank can propagate *down* to the lowest rank is due to the closedness and the hierarchical nature of military organisation.

There are dashed inter-rank links, e.g., from Instructor_a to Officer_b¹. These dashed inter-rank links represent a possible situation where the instructor rank is two-rank above that of trainees. These dashed links, in principle, can trigger the loops in higher echelons and form *inter*-rank feedback loops via the promotion links. The fact that increased training demand at a low rank can cascade *up* to higher ranks to form *inter*-rank loops, is again due to the closedness and the hierarchical nature of military organisation.

¹ Strictly speaking, the link should be from Instructor_a to CF Officer_b. The connection shown crosses fewer other links and does not change the implication.

Having analysed qualitatively the complexity in managing a military training system, we present a simulation model based on SFD to further explore the link between loop structure and the time evolutionary behaviour of the system, to answer ‘what if ...’ questions when the system experiences disturbances, and to find guiding policies which can shape the system behaviour[7, 29].

4. The System Dynamics Simulation Model for the Military Workforce

The CLD analysis in the previous section revealed the following features of the military workforce:

1. Changes in training demand at a high rank can spread down to all lower ranks because of promotion;
2. Changes in training demand at a low rank, depending on the rank of instructors required, could, in principle, cascade up to higher ranks by shifting CF officers to work as instructors; and
3. The intention to expand the CF will result in its transient reduction because of, again, shifting CF officers to work as instructors.

In order to quantitatively investigate the impacts of the above features on the dynamic behaviour of the workforce, we now construct an SD simulation model.

4.1 Stocks, flows and delays in building an SD simulation model

There are three ingredients in SD simulation modelling: stocks, flows and delays.

Stocks are the accumulation of their net inflows over time and can be defined mathematically by the following integral equation:

$$S(t) = \int_{t_0}^t \text{netflow}(s) \cdot ds + S(t_0) \quad (1)$$

where $\text{netflow}(s) = \text{Inflow}(s) - \text{Outflow}(s)$, with $\text{Inflow}(s)$ and $\text{Outflow}(s)$ denoting the values of the inflow and outflow for the stock variable S at any time s between the initial time t_0 and the present time t [15]. In practice, stock variables are calculated numerically by the following Euler integration method [3]

$$S_k = S_j + dt \cdot (\text{netflow})_{jk} \quad (2)$$

that is, the value of stock at the current time k equals its value at the previous time j (with $t_0 \leq j, k \leq t_{\max}$, t_{\max} denoting the simulation length), plus the net flow over the interval (dt) that has passed since the last time point [5]. SD software such as Powersim will generate the stock equations once modellers assign the initial value S_0 and connect the inflow or outflow to the stock in SFD.

Flows are the driving forces for changes in stocks. In general, flow variables depend on the stocks, auxiliary variables and other system parameters. The general definition is [3]:

$$\text{Flow}_{kl} = f(S_k, \text{Auxiliary}_k, \text{Parameters}) \quad (3)$$

which states that the value of flow during the time interval (dt), i.e., the interval from present time k to the next time point l , is a function of the present values of stock S_k , auxiliary variable $Auxiliary_k$, and some other parameters. Note that the flows are kept constant during the time interval (dt) and are only updated after the next calculation of stock and auxiliary at the time point l [5]. As was mentioned in section 2.1, SD modelling focuses on the modelling of flows to explore policies. It is the modellers' responsibility to specify the function forms for flow variables to simulate current policies, or to design new policies for management intervention.

Besides the stock and flow variables in SFD, another type of component in building an SD simulation model is delays which are defined as time lags between inputs and outputs [15]. Delays can have a great influence on system performance. Two types of delays encountered in SD modelling are material delays and information delays. Material delays refer to processes in transforming the system physical resources [19] (e.g., the training processes in converting recruits into qualified officers with delay specified by training time). Information delays are the processes in perceiving, transmitting, statistical averaging and acting on information [19] (e.g., the graduation percentage and officer leaving percentage are delayed information because they are obtained by statistical analysis of historical data). Powersim software offers several intrinsic functions to model material and information delays.

Having sketched the essential elements in an SD simulation model, we now describe the hypothetical four-rank military workforce.

4.2 The four-rank military workforce

The system to be simulated is a four-rank military workforce. The system recruits a -rank trainees from outside and trains insiders for promotion. It is assumed that while failed a -rank trainees exit the system, failed higher rank trainees return to their original ranks to continue their service. The steady state of the training force is specified by the parameters shown in Table 1.

Table 1. Steady State parameters

| Rank (λ) | a | b | c | d |
|--|------|------|------|-----|
| Number of CF Officers | 2000 | 1500 | 1000 | 500 |
| Number of Instructors | 57 | 34 | 17 | 6 |
| Officer Leaving Percentage l_λ | 10% | 10% | 10% | 10% |
| Graduation Percentage (g_λ) | 90% | 90% | 90% | 90% |
| Instructor/Trainee Ratio (r_λ) | 0.1 | 0.1 | 0.1 | 0.1 |
| Training Time (Year) | 1 | 1 | 1 | 1 |

For simplicity, we assume that the yearly separation percentage l_λ , training completion percentage g_λ , instructor to trainee ratio r_λ and the training time are uniform across all four ranks. We believe the simplification will not alter the discussion and conclusions presented later, since the focus of the present work is the relationship between the system loop structure and the broad behaviour of the system.

We also assume that the instructor rank is one rank above the rank of trainees, which is an acceptable assumption according to TC-A. With this assumption, there is no spread-up effect of training demand, because the inter-rank loops in Figure 1 do not exist. The model does not consider instructor training² and assumes that the CF is the source of instructors, which is the scenario presented by TC-A.

We will simulate the system response under different policies when the steady state is disturbed by a demand of 20% step increase of extant CF officers from the year 2015.

4.3 The SD simulation model

The SD simulation model has a front page with hyperlink buttons to access different pages as illustrated in Figure 4.



Figure 4. The front page of the SD simulation model with hyperlink buttons

Besides the CLD page to communicate the system loop structure, the model has input pages for user inputs and output pages with outcomes presented in tables and graphs. Figure 5 shows the input page for parameters to specify the training section.

There is a similar page to input officer-related parameters, such as leaving percentages. Appendix A shows the complete SFD.

² It is not difficult to include instructor-training courses in the model if it is necessary. An SD model and a DE model have been constructed to investigate the fast-jet pilot training system which includes qualified-flying-instructor training [30].

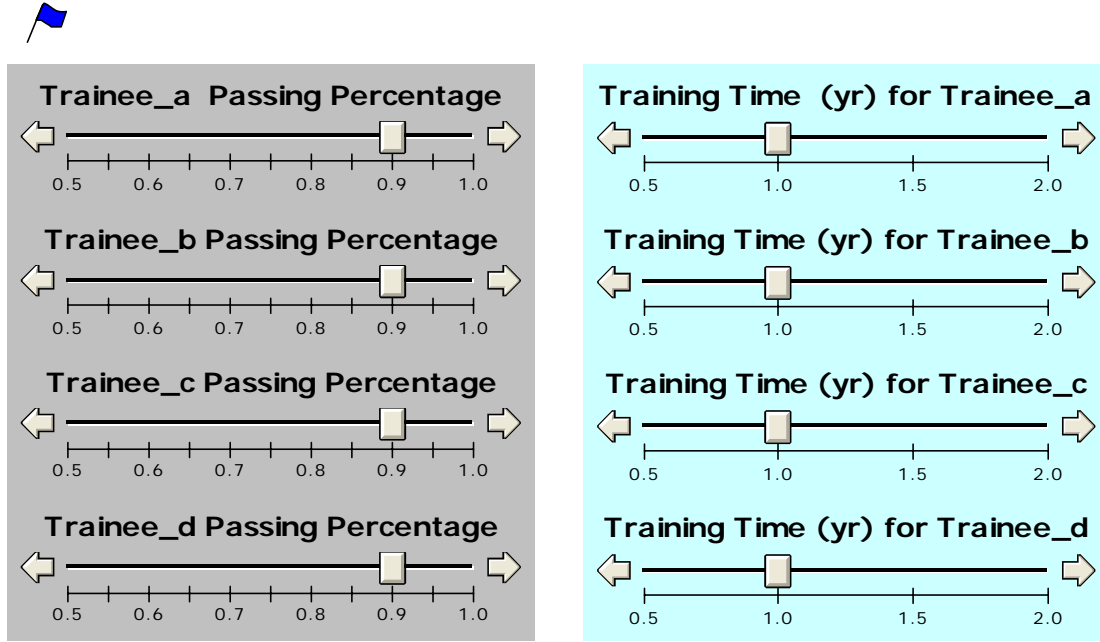


Figure 5. Part of the input page for training-related parameters

We next present the simulation results.

4.4 Potential applications of the SD simulation model

In this section, the potential applications of the SD simulation model are demonstrated. The SD model is first applied to determine optimal policies for a robust workforce when the system is 'shocked' by an expansion demand. Under the proposed policy, the model is then applied to examine the system response to other disturbances, such as insufficient new recruits or fluctuations in officer separation rates. Finally, with the proposed policy and warranted human resources, the model is used as a human resource planning tool for expanding a military organisation.

4.4.1 The application in policy analysis

As mentioned previously, policies are decision rules representing how the information is used to specify actions to achieve the system goal. The goal of the training system is to maintain the defence workforce at a desired level. Therefore, the policy should specify how many people are required for training. Mathematically, we need to write the equations for the flows of recruitment and promotions.

We list the following possible control policies to test the system response:

- Leaving control³ [14], which is the number of trainees needed to replenish the expected vacancies due to separation. We have, for the λ rank ($\lambda = a, b, c, d$), $C_{leave}^{\lambda} = Expected_Separation_{\lambda} \approx l_{\lambda} \times Officer_{\lambda}$, where $Officer_{\lambda}$ is the actual number of officers, and l_{λ} is the leaving percentage given in Table 1. Notice that we have assumed in this report that the expected separation is the same as the actual separation, an acceptable approximation as long as this outflow is directly

³ This control is called Inertial Control in [14].

observable by decision makers with essentially no delay [15]. More accurate C_{leave}^λ can be obtained by a weighted average, such as exponential smoothing [14, 15].

- Promotion control, which is the number of trainees needed to replenish the expected vacancies due to promotion. We have, for the λ rank ($\lambda = a, b, c$), $C_{prom}^\lambda = promotion_\lambda$, where $promotion_\lambda$ is the inflow for the stock of $(\lambda + 1)$ -rank trainee, i.e., the number of λ -rank officers to be trained for promotion.
- Proportional Control [3, 14], which is the number of trainees needed to eliminate the gap between the desired and the actual numbers of officers. We have $C_{prop}^\lambda = (Desired_Officer_\lambda - Officer_\lambda) / Time_to_adjust_\lambda$, where $Desired_Officer_\lambda$ is the number of officers required in the rank. The time parameter, $Time_to_adjust_\lambda$ is the possible time delay in recruiting trainees and can be used to model resource constraint, e.g., $Time_to_adjust_\lambda = 2$ (years) means only half of the required trainees could be recruited per training year. Notice that the strength of this control is proportional to the magnitude of the gap to be controlled [3].
- Pipeline control[14], which is the action to maintain the number of trainees (that is, those in the 'pipeline') at the desired level. This control adjusts the number of trainees *to be* trained by taking into account those *being* trained. We have, $C_{pipe}^\lambda = (Desired_Trainee_\lambda - Trainee_\lambda) / Time_to_adjust_\lambda$, where the desired number of trainees is determined by:

$$Desired_Trainee_\lambda = Training_Time_\lambda \times Expected_Separation_\lambda.$$

The inflow equation for stock variables $Trainee_ \lambda$ in the SD simulation model is⁴

$$Inflow_ \lambda = (C_{leave}^\lambda + g_{\lambda+1} C_{prom}^\lambda + C_{prop}^\lambda) / g_\lambda + switchpipe \times C_{pipe}^\lambda \quad (4)$$

where the parameter *switchpipe* is introduced to test the effect of the pipeline control.

Intuitively, it seems we do not need pipeline control to keep the workforce at the required level because the first three controls in Equation (4) will fill vacancies due to separation and promotion, and eliminate any possible gaps. Therefore, a naïve policy would simply neglect the pipeline control, i.e., $switchpipe = 0$. With the naïve policy, even without any constraints on human resources, the SD model depicts the system response to a demand of a 20% one- step increase of the current CF officers in all four ranks at the year 2015, shown in Figure 6.

Figure 6 shows that the consequence of the naïve policy. The horizontal part represents the current steady state. There are oscillations in all four-rank trainees due to omitting the pipeline control. The oscillations in the numbers of trainees lead to the swing of the officers between the CF and the Training force, shown in Figures 7 and 8.

⁴ In the SD model presented, the variable name *Inflow* is replaced by *Recruit* for rank *a*, and by *Promotion* for other ranks.

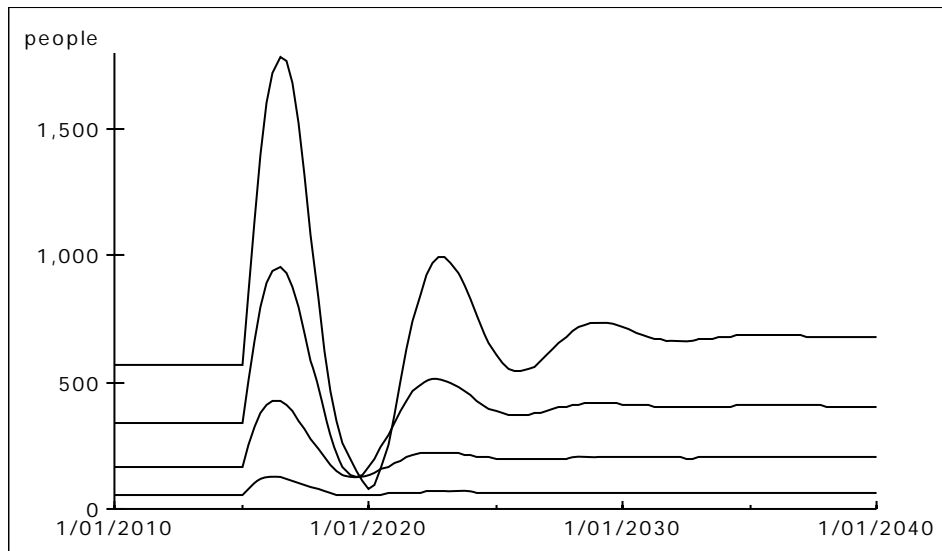


Figure 6. The time variation of numbers of trainees under the naive policy. The top curve is the number of a-rank trainees and the three lower curves are for higher ranks with the lowest curve for rank d.

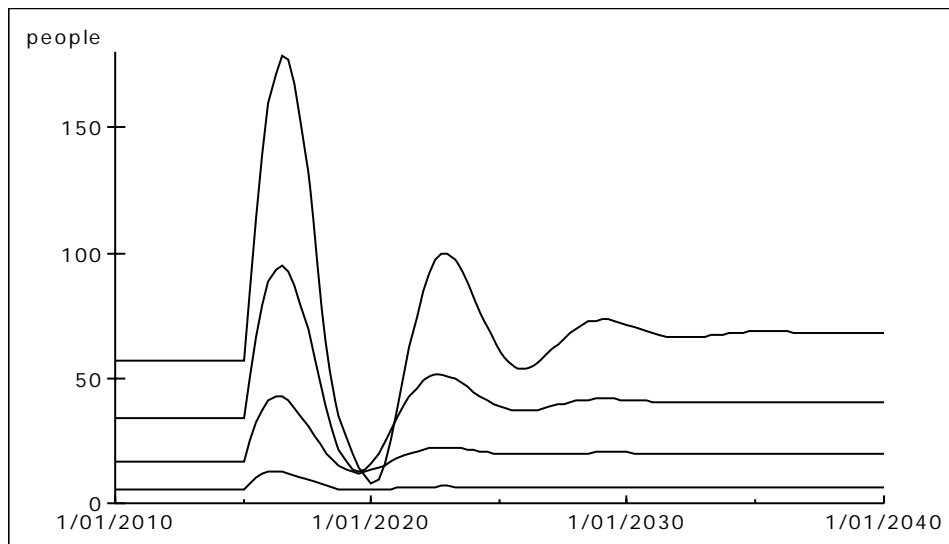


Figure 7. The time variation of numbers of instructors under the naive policy. The top curve is the number of instructors for a-rank trainees and the other three curves are numbers of instructors for higher ranks with the lowest curve for d-rank instructors.

Figure 7 indicates that the numbers of instructors fluctuate to match the fluctuation in trainee numbers. Collectively, the oscillations in numbers of trainees and instructors result in the overshoot and undershoot in the numbers of CF officers shown in Figure 8.

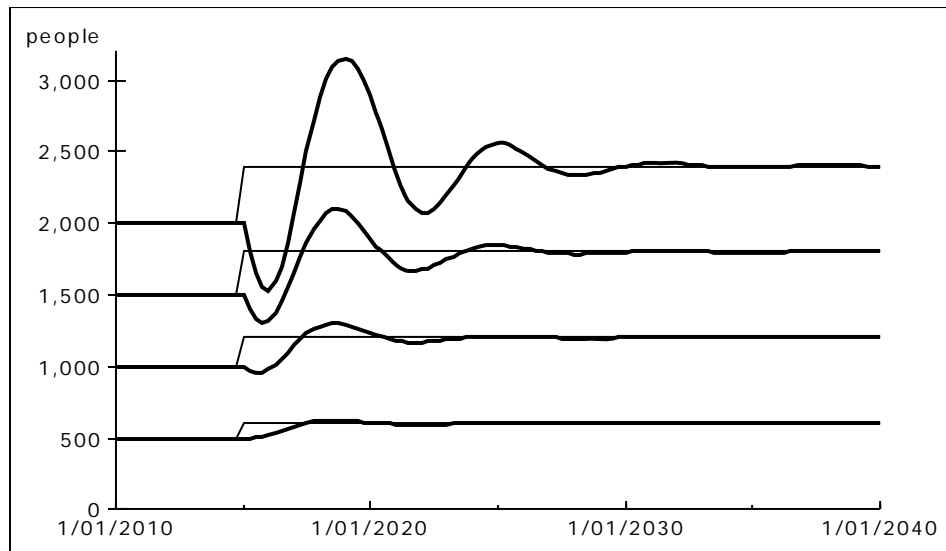


Figure 8. The responses of CF stock variables when the system policy does not include pipeline control.

The thin lines are desired numbers of CF officers, the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The top curves are for *a*-rank and the lower curves for higher ranks with the lowest curve for *d*-rank.

Figure 8 predicts that, even though the demands – the desired numbers of CF officers – follow step functions and do not oscillate, a naïve policy can lead to oscillating behaviour in the CF workforce. While the system finally settles down at the desired new steady state, the CF officer-resource overshoots and undershoots the targeted workforce level, even if all human resources are warranted. The worst case is for the *a*-rank personnel which suffers overstocking as high as 33% of planned workforce and takes about 20 years to stabilise at the new steady state. It is interesting to note that the amplified oscillations and prolonged restoration period to new steady state worsen as the rank goes lower, which is similar to the order amplification [15] or the bullwhip effect [31, 32] encountered in supply chain management [15, 33].

A supply chain is simply defined as ‘the set of structures and processes an organisation uses to deliver an output to a customer’ [15]. Products in a supply chain flow through various stages, from the upstream end as acquired raw materials, through processing stages experiencing transformations, then to the downstream end in the form of customer-required products. The order amplification [15] or bullwhip effect [32] is the increase of order fluctuations going up the stream, away from the customer toward the supplier. Here, the military training system supplies qualified officers as its product, with the *a*-rank training acting as the supplier role. While research is still ongoing to explore various techniques to mitigate or eliminate the instability in the management of business supply chain [32, 34, 35], we simply switch on the pipeline control as the counter measure.

With the pipeline control, i.e., *switchpipe* = 1 in Equation (4), the SD model forecasts the system response shown in Figure 9, Figure 10 and Figure 11.

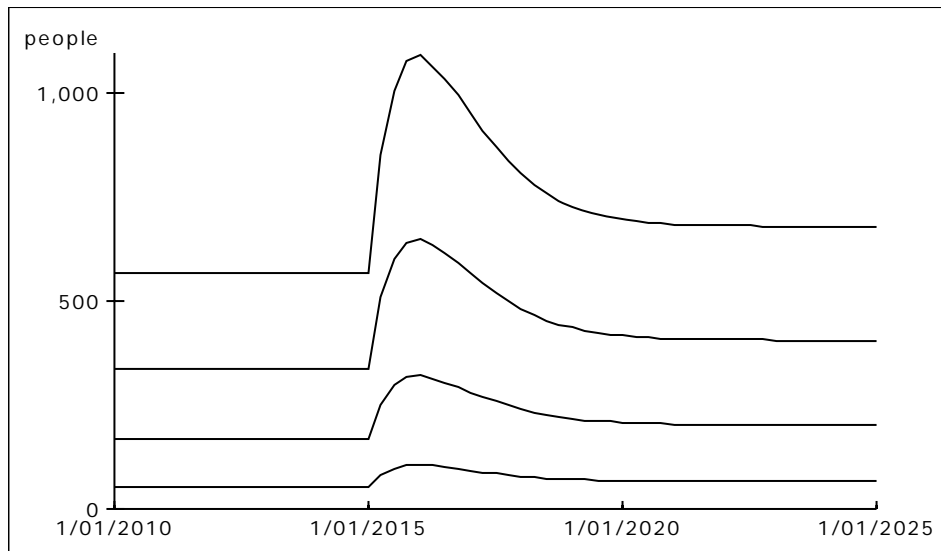


Figure 9. The time variation of numbers of trainees with the pipeline control. The top curve is the number of a-rank trainees and the other three lower curves are for higher ranks with the lowest curve for rank d.

Figure 9 displays the behaviour of trainee stocks under the policy with pipeline control. There are no oscillations in the numbers of trainees at all four ranks. Four curves illustrate that the numbers of trainees required will first jump to satisfy the step increase in CF demand and then decrease towards the new steady state. Figure 10 shows the requirement for instructors.

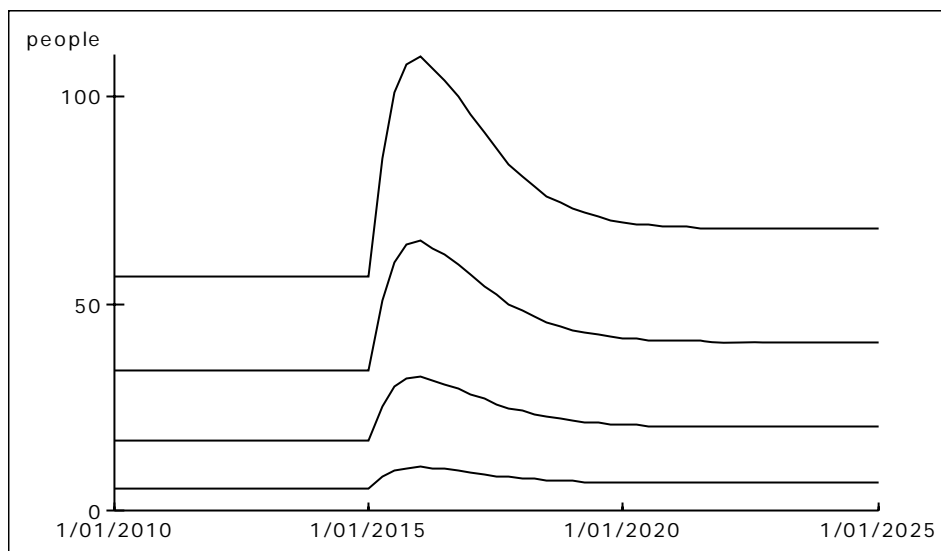


Figure 10. The time variation of numbers of instructors with the pipeline control. The top curve is the number of instructors for a-rank trainees and the other three curves are numbers of instructors for higher ranks with the lowest curve for d-rank.

The variations in instructor stocks in Figure 10 follow the changes in trainee stocks. Note that, in order to sustain the CF at the new steady state, the instructor stocks are stabilised at new higher levels to suit the increased training requirement. Collectively, the end result in CF personnel shown in Figure 11 could be expected.

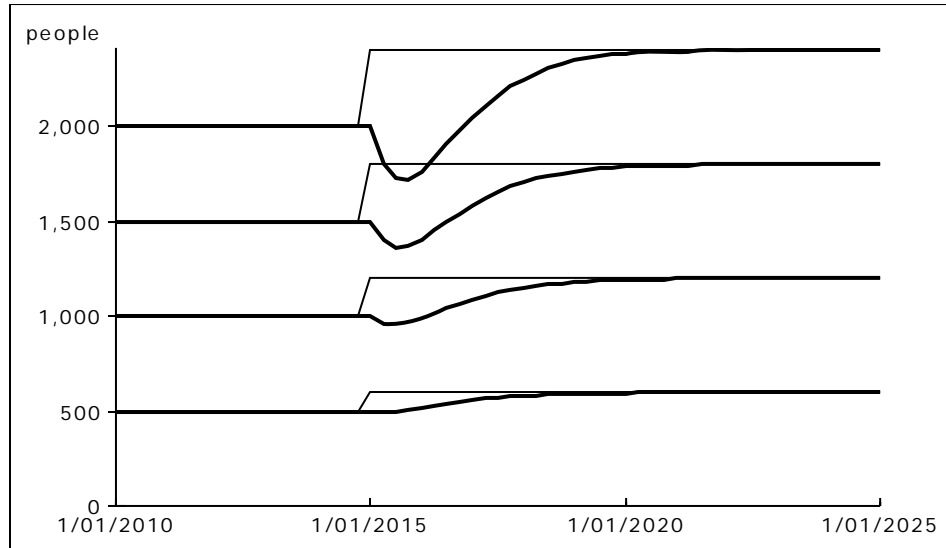


Figure 11. The responses of CF stock variables when the system policy includes pipeline control. The thin lines are desired numbers of CF officers, the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The top curves are for a-rank and the lower curves for higher ranks with the lowest curve for d-rank.

Figure 11 shows that the CF experiences temporary reduction in its workforce in all four ranks⁵ because some of the CF officers leave service for promotion training and some of the CF officers become instructors. This temporary reduction is due to the closed nature of the military organisation as analysed by CLD in section 3. As more trainees graduate, the CF workforce approaches its desired level without any fluctuations.

The difference between the system responses without and with the pipeline control, in Figure 8 and Figure 11, is considerable. Therefore, the advice for the training management from the SD model is ‘never forget the pipeline control’.

For the policy with the pipeline control, we now examine the system response when some of the human resources are constrained.

4.4.2 The application to answer ‘what if ...’ questions

In this section, we investigate what would happen to the system if some parameters deviate from their expected values.

First, we check the system response when the resources of trainees are constrained. More specifically, we let $Time_to_adjust_{\lambda} > 1$ (year) in the proportion control and the pipeline control in Equation (4). This means that only $1/Time_to_adjust_{\lambda}$ of trainees needed can be provided. The following result shows the system response when $Time_to_adjust_a = 3$ (years).

⁵ The reduction in d-rank CF personnel is not noticeable because of the scale in the graph.

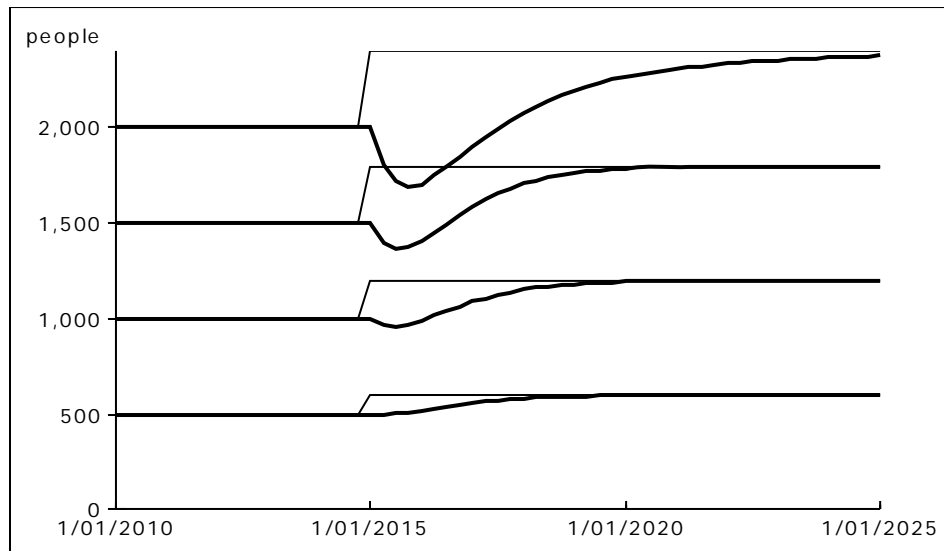


Figure 12. The responses of CF stock variables when the system policy includes pipeline control. The thin lines are desired numbers of CF officers, the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The number of available *a*-rank trainees is constrained by setting the parameter $Time_to_adjust_a = 3$. The top curves are for *a*-rank and the lower curves for higher ranks with the lowest curve for *d*-rank.

When only a third of required *a*-rank trainees could be recruited, Figure 12 displays a lengthened transition period to approach the new steady state for *a*-rank by the top curve. The other three curves for higher ranks display the same behaviour as those in Figure 11, which is expected since the higher rank resources are still assured.

We next vary the officer leaving percentage l_λ in Table 1 from its given value. The leaving percentages are modelled as exogenous elements. Exogenous elements affect other elements in the system, but are not themselves affected by others [19]. More specifically, the leaving percentage for the *c*-rank l_c jumps from 0.1 to 0.2 for two consecutive years starting from 2015. Figure 13 displays the assumed function for l_c . Figure 14 shows the pattern of change in CF officer stocks.

Even if the system policy includes pipeline control, Figure 14 shows that CF officer resources at all three lower ranks overshoot the expansion goal and then approach the new steady state without any further oscillation. The overshooting could be attributed to the time delay in acquiring the separation information and the time delay for the system to adapt itself to the newly acquired information. The information about the separation is unavoidably delayed because it needs time to collect data. It is also delayed by the time to recruit and train people for the system to recover from the separation fluctuation. The following description helps to explain the overshoot: the promotion of *b*-rank is increased after the system perceives the increase in *c*-rank separation, which results in more *c*-rank trainees. After the *c*-rank separation is reduced to its original value 0.1, the *c*-rank graduates fill fewer than the expected vacancies, which results in overshooting. It is interesting to note that the disturbance in *c*-rank separation spreads down to the lowest *a*-rank, which is again due to the closedness and the hierarchical nature of military organisation as explained in section 3. The *d*-rank officer stock is not affected because of the assumption that instructor rank is one above the trainee rank.

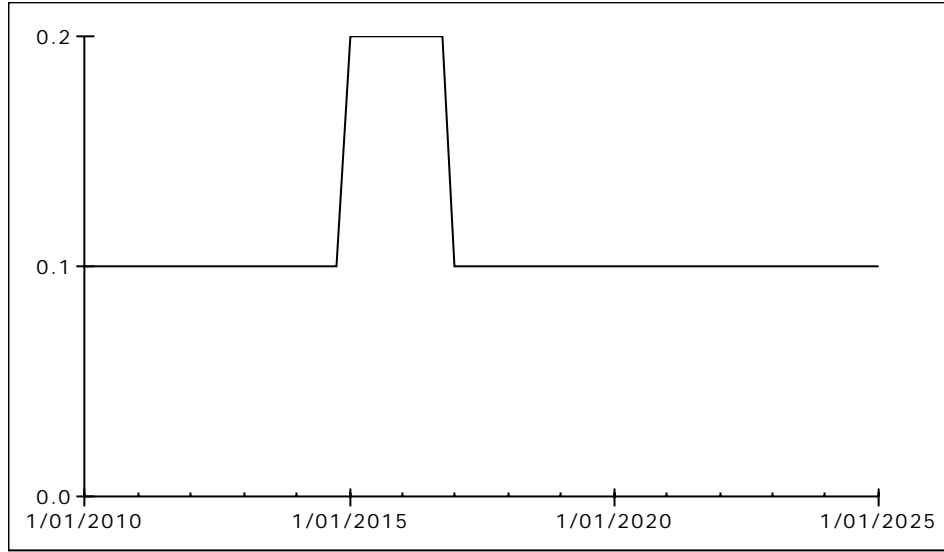


Figure 13. The assumed function form for the leaving percentage of c-rank officers l_c . It is assumed that l_c jumps from its average value 0.1 to 0.2 during the period 2015 to 2016.

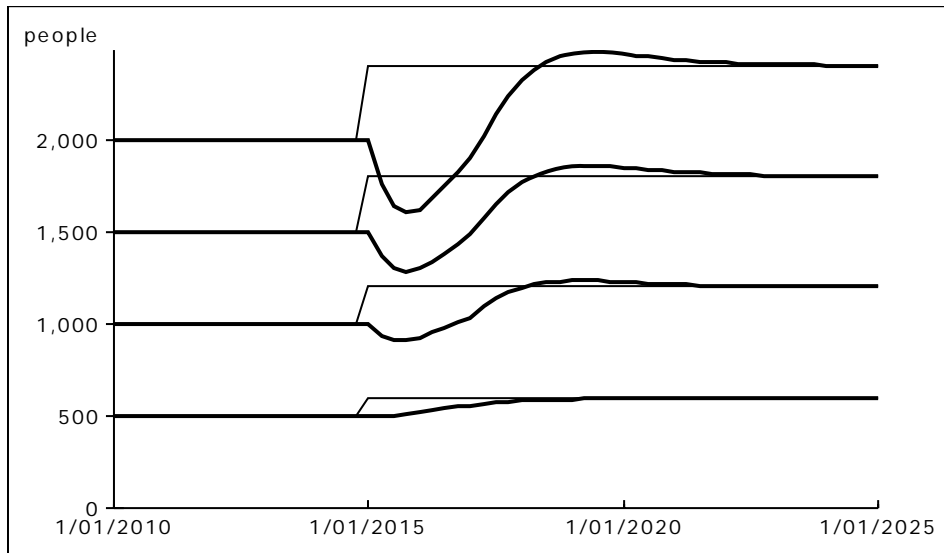


Figure 14. The responses of CF stock variables when the system policy includes pipeline control. The thin lines are desired numbers of CF officers, the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The leaving percentage l_c is given in Figure 13 and other three leaving percentages l_λ ($\lambda \neq c$) are still kept at the average value 0.1. The top curves are for a-rank and the lower curves for higher ranks with the lowest curve for d-rank.

Next, we demonstrate that the model could be used as a planning tool to expand a military organisation.

4.4.3 The application as a planning tool

As a continuous simulation, SD uses time-slicing, with equal time interval dt [5]. Within the simulation, every variable is updated every time interval. This treats the flow variables such as recruitment and graduation as continuous. This is an approximation since, in reality, recruitment and graduation only happen at discrete points of time. In previous discussions, we have set $dt=0.25$, a value small enough so that final results are not altered when dt is further reduced.

When the model is used as a planning tool to expand a military workforce, we need to model the discreteness to calculate the training demand accurately. There are several ways to express discreteness in SD [36], One way is to make explicit use of the time step dt [36]. We set the magnitude for the time interval $dt=1$, the same as the training time, to model discrete flows. The stock variables are only updated yearly by the discrete flows in recruitment, graduation and separation. Mathematically, the Euler integration in equation (2) becomes a pure summation when $dt=1$.

Assume that there is a demand for 20% increase of the current b-rank CF officers while the CF workforce at other three ranks is kept constant. The SD model produces the plan shown in Figure 15.

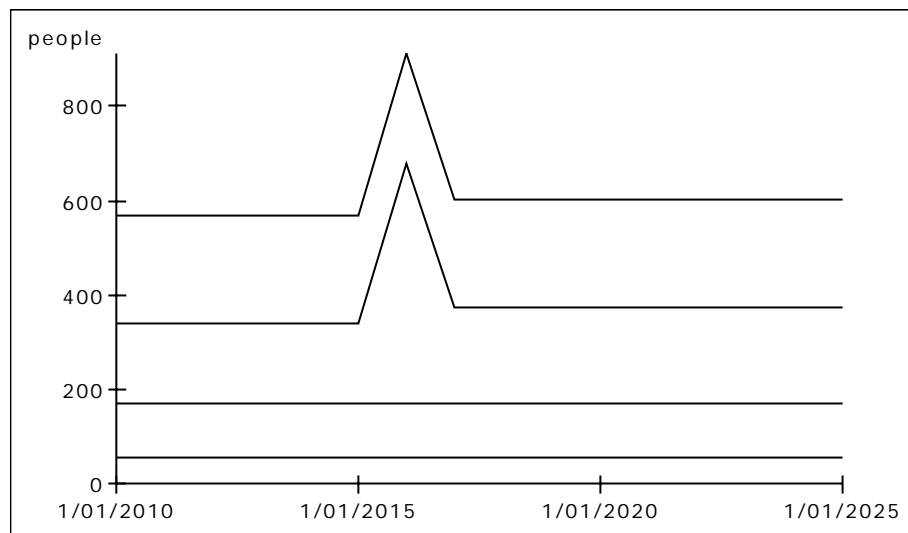


Figure 15. Required numbers of trainees for 20% increase of extant b-rank CF officers. The top curve is the number of a-rank trainees and the three lower curves are for higher ranks with the lowest curve for rank d.

Figure 15 displays the required trainee-resources to achieve the expansion target. The required trainees for c and d ranks are kept at the current level to sustain the c and d rank workforce at the steady state. The number of b-rank trainees, the second curve from the top, first jumps to meet the expansion need and then falls to settle at a level higher than the extant value to sustain the expanded b-rank workforce. Although there is no expansion requirement for the a-rank workforce, the a-rank trainee curve follows the trend of b-rank curve in response to the increased promotion request to sustain the present a-rank workforce. Figure 16 shows the required instructor resource.

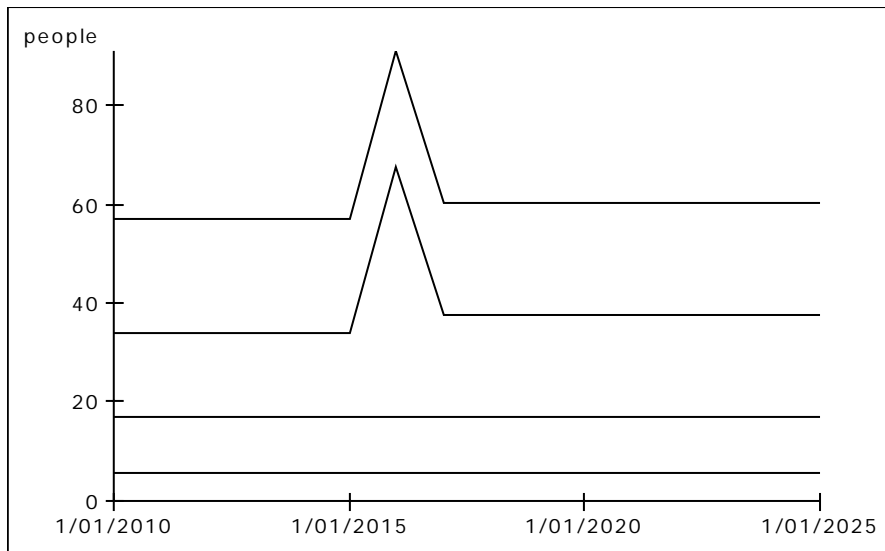


Figure 16. Required numbers of instructors for 20% increase of extant b-rank CF officers. The top curve is the number of instructor for a-rank trainees and the three lower curves are for higher ranks with the lowest curve for rank d.

Figure 16 shows the instructor resource that TC-A requires to train the trainees in Figure 15. The instructor curves follow the patterns of trainee curves as expected, since they are proportional to the numbers of trainees. Figure 17 shows the CF workforce delivered by the above plan, given assured human resources.

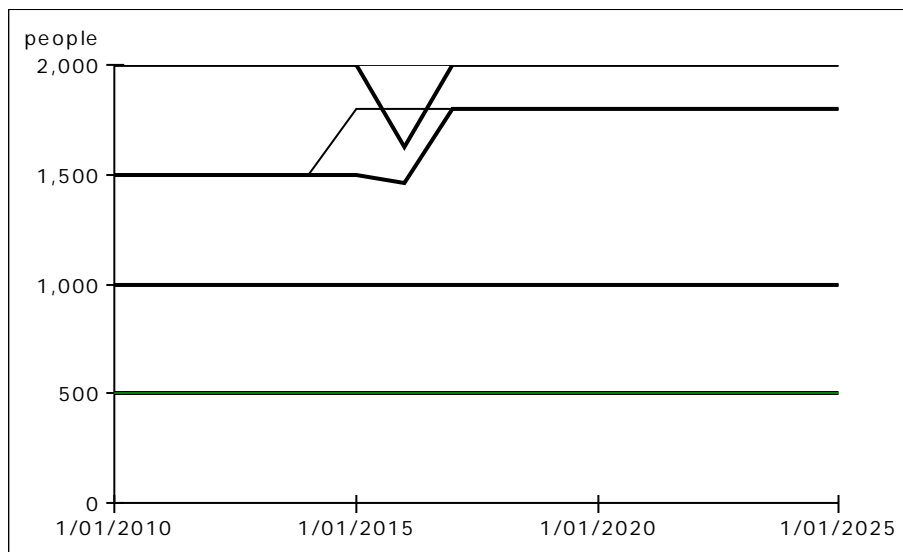


Figure 17. The responses of CF stock variables to a demand of 20% increase of extant b-rank CF officers.

The thin lines are the desired numbers of CF officers given the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The top curves are for a-rank and the lower curves for higher ranks with the lowest curve for d-rank.

In Figure 17, the c-rank and d-rank workforce, represented by the two horizontal lines, are not disturbed by the b-rank expansion. The b-rank workforce has a slight drop at first, corresponding to the transfer of b-rank CF officers to work as instructors, then achieves the expansion target. Note that, while the a-rank workforce is intended to

remain constant, there is a temporary reduction in a -rank officers. The dip in the a -rank curve is deeper than that in the b -rank curve, because the a -rank workforce has to provide both extra instructors and extra b -rank trainees for promotion training.

Next, we consider a demand for 20% increase of d -rank CF officers while the CF workforce at other three ranks is kept constant. Figure 18 shows the plan produced by the SD model.

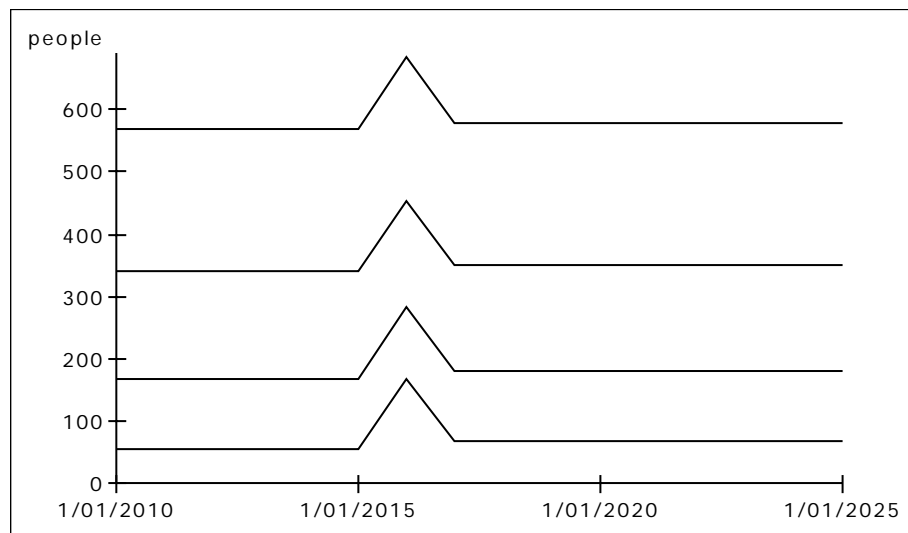


Figure 18. Required numbers of trainees for 20% increase of extant d -rank CF officers. The top curve is the number of a -rank trainees and the three lower curves are for higher ranks with the lowest curve for rank d .

Figure 18 displays the required trainee resource to achieve the expansion goal. There are increased training demands for all four ranks, even though only the d -rank workforce is required for expansion. The number of d -rank trainees, shown by the fourth curve from the top, jumps first to meet the expansion need and then falls to settle at a level higher than the extant value to sustain the expanded d -rank workforce. The other three curves follow the trend of the d -rank curve to meet the increased promotion demand, even though there is no request for expansion at the lower levels.

Figure 19 shows the instructor resource that TC-A needs to train the trainees in Figure 18. There is a demand to increase instructor resource at all four ranks, though only the d -rank workforce is required for expansion.

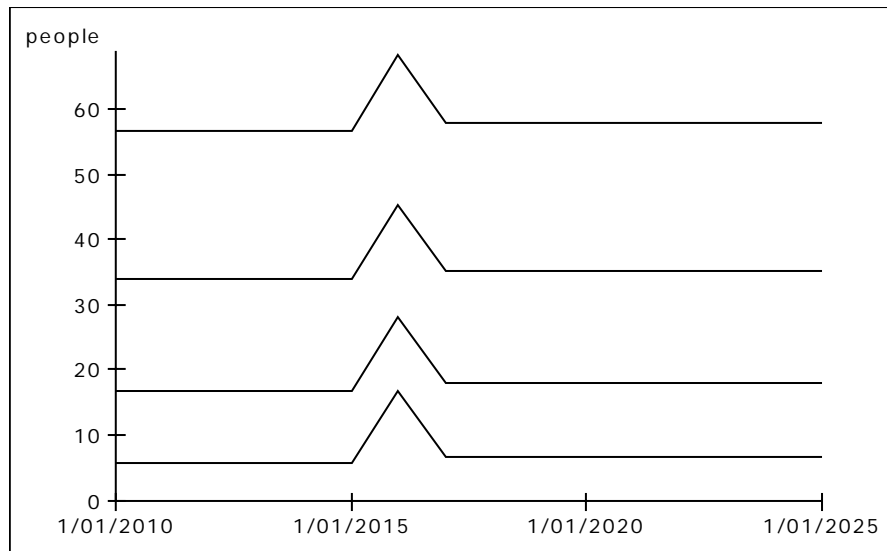


Figure 19. Required numbers of instructors for 20% increase of extant d-rank CF officers. The top curve is the number of instructor for a-rank trainees and the other three lower curves are for higher ranks with the lowest curve for rank d.

With the above plan, the SD model depicts the profile of the expected CF workforce shown in Figure 20.

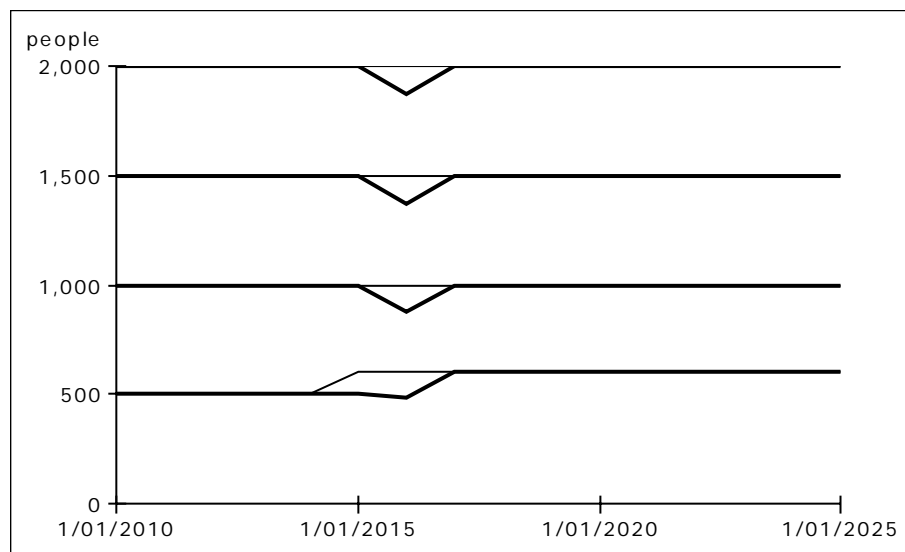


Figure 20. The responses of CF stock variables to a demand of 20% increase of d-rank CF officers. The thin lines are desired numbers of CF officers, the demand for 20% increase of extant CF workforce. The thick lines are the time variation of CF officer stocks. The top curves are for a-rank and the lower curves for higher ranks with the lowest curve for d-rank.

Figure 20 shows that the CF workforce experiences a transient reduction in the expansion training year at all four ranks. As more graduates are delivered, the workforce at the three lower ranks returns to and stays at their extant levels, while the d-rank workforce is expanded and sustained at the targeted strength.

5. Summary

This report presents an SD simulation model to analyse the training management system in a four-rank military workforce.

Starting from the generic properties of any military organisation, i.e., closedness and hierarchy, a CLD portrays the feedback structure for the four-rank military workforce. Based on the CLD constructed, a detailed intra-rank and inter-rank loop analysis exposes the possible impacts of feedback structure on the system performance (section 3). The system response is examined when the workforce experiences an external disturbance such as a demand for expansion (section 4). The CLD depicts the following consequences of the closedness and the hierarchical nature:

- An increased training demand at a high rank can cause increased training demands at all lower ranks ;
- The intention to expand the CF workforce could lead to its temporary reduction; and
- Depending on the instructor rank-structure, an increased training demand at a low rank can, in principle, cause increased training demands at higher ranks.

The SD simulation model is used for quantitative analysis of a fictitious four-rank military workforce. The utility of the SD model is demonstrated in three aspects:

- The model shows that a naïve policy can lead to a bullwhip effect: the amplified oscillating behaviour in CF workforce even though the expansion target follows step functions which do not oscillate;
- When the human resource is constrained or a system parameter deviates from its average value, the model shows its applicability to answer ‘what if ...’ questions; and
- Finally, the model is useful as a planning tool to expand a military organisation.

The SD simulation model is adaptable to changing parameters, such as updated separation rates or different instructor-to-trainee ratios and can be modified to model different trades with different instructor-rank structures. With some modification, the SD model in this paper may possibly be incorporated as part of normal Army long-term workforce planning, and is also relevant to other branches of Defence.

The model offers the workforce planners an analytic tool to test different policies to learn what effects they have on the workforce [37].

6. Acknowledgements

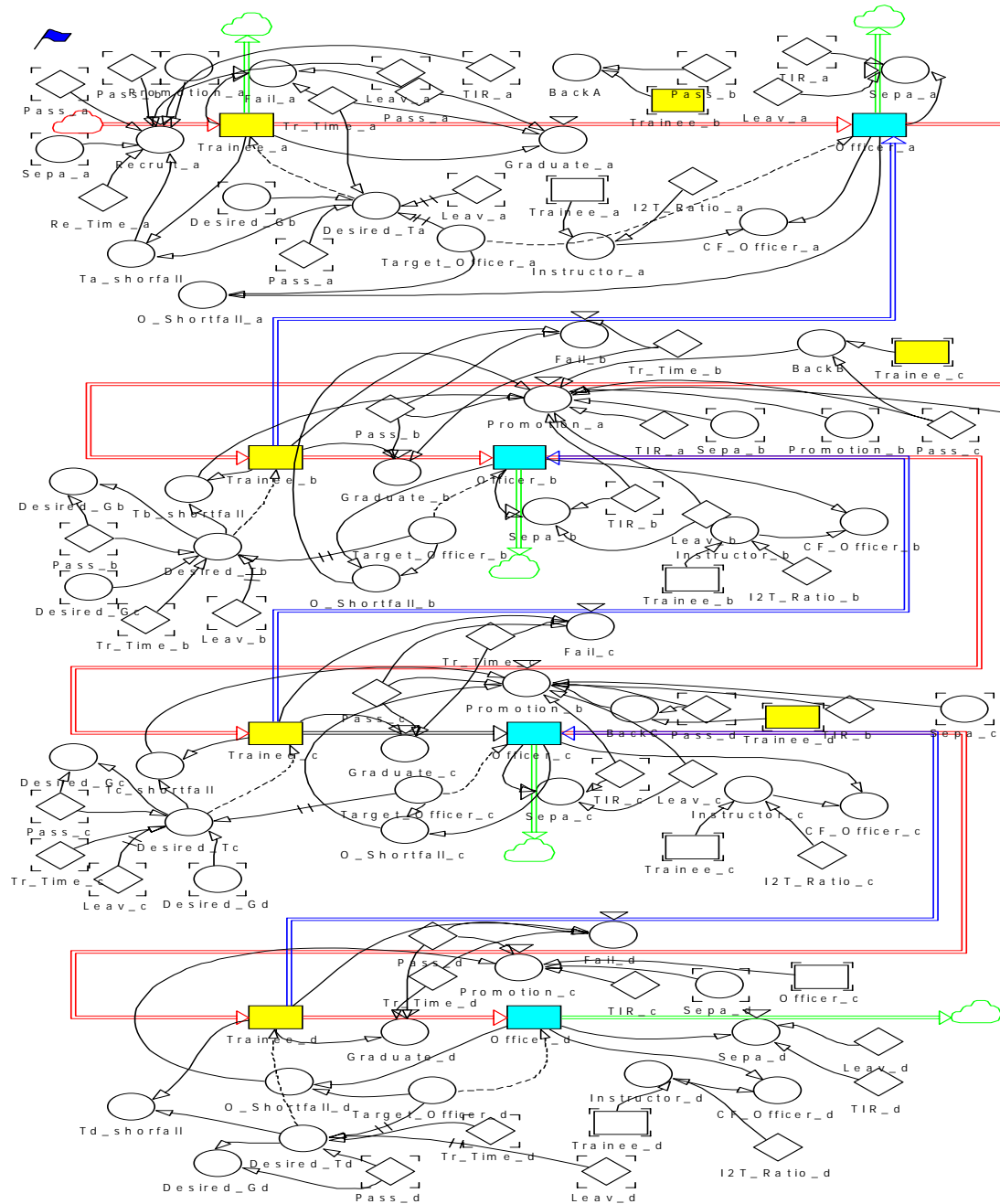
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Appendix A: The Stock Flow Diagram of the SD Simulation Model for the Four-Rank Military Workforce



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| 17. CITATION IN OTHER DOCUMENTS Yes | | | | | |
| 18. DSTO Research Library Thesaurus <div style="margin-left: 40px;"> Force structure Military planning Simulation Work study analysis </div> | | | | | |
| 19. ABSTRACT This report presents a system dynamics simulation model for a four-rank military workforce, that includes both the combat and training components. A qualitative analysis using a Causal Loop Diagram displays the feedback loop structure of the workforce and its impacts on the management of training. The simulation model is applicable to strategic training policy design and analysis, in answering 'what if ...' questions, and workforce planning in expanding military organisations. | | | | | |